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Dynamic control of photonic bandgap mediated by vacuum-induced coherence

M.A. Antón, F. Carreño *

Escuela Universitaria de Óptica, Universidad Complutense de Madrid, C/ Arcos de Jalón s/n, 28037 Madrid, Spain

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ABSTRACT

We theoretically examine the storage and retrieval of a light pulse in a medium comprised of four-level atoms of the $V-\Lambda$-type. The two intermediate levels are probed by a weak field and vacuum-induced coherence effects lead the system to transparency. The temporal variation of the intermediate levels' splitting is used as an external parameter which allows the transfer of the impinging field to a combination of spin coherences. An auxiliary and far-detuned control field in a standing-wave configuration is used to induce a variable photonic bandgap by cross-phase modulation. It is shown that dynamic control of such a bandgap can be used to coherently manipulate the previously stored probe pulse. We use a general scheme to take into account multiwave mixing effects and solve the combined Maxwell–Bloch equations for the relevant coherences. It is shown that the system acts as an all-optical router.

1. Introduction

Different emergent technologies like integrated all-optical signal processing and all-optical quantum information processing share a common requirement concerning the switching and storage of light pulses in a controlled way. Photons can be considered as the most natural carriers of information with its benefits of ultrafast and noninterference characteristics, while atomic systems are expected to provide the best resources for their storage and manipulation. However it is extremely difficult to store photons for a long time and retrieve them from a medium on demand.

Several theoretical proposals have tackled the transfer of quantum states of light to matter excitations. Early work focused on the use of individual atoms as quantum memory elements [1]. However, it was recently realized that quantum state transfer could be simplified by using atomic ensembles rather than single atoms [2–4] and have been implemented for storage of classical and non-classical light pulses [5–7]. These proposals typically rely on electromagnetically induced transparency (EIT) phenomenon [8,9]. Specifically, it has been shown both theoretically and experimentally that a light pulse propagating through a medium comprised of three-level atoms in the Λconfiguration, suitably driven by another auxiliary field, can be stopped and latter released in a controlled way (see the review in ref. [10]). Storage and retrieval of light fields mediated by spin coherence wave packets in atomic samples are now practical laboratory routines [11–15]. The process is interpreted in terms of inducing transient Raman coherence between the two lower atomic states or in terms of an adiabatic evolution of the so-called dark-state polariton. Storage and retrieval of single photons have been reported using EIT in cold atomic clouds [16], thermal gases [17] as well as in solid media [18]. Examples of four-level systems such as double-Lambda, tripod [19] and inverted-Y atomic systems [20], have recently been discussed in the context of light storage.

However, there is another way of generating coherence which is based not in coherent driving fields but on a dissipative process such as spontaneous emission. In an early study, Agarwal [21] showed that an initially excited degenerate V-type three-level atom may not decay to its ground level due to a complete cancellation of spontaneous emission. If the two upper levels are very close and damped by the usual vacuum interactions, spontaneous emission cancellation can take place, which offers the possibility to trap population in the excited levels when some particular conditions hold [22–28]. Quantum interference between the two transition channels connecting the ground level, the so-called vacuum-induced coherence (VIC), is responsible for many novel effects, such as narrow resonances and probe transparency [29], dark spectral lines [30], phase dependent line shapes [31,32], gain features on dark transitions [33–36], among others.

The aim of this paper is to extend the ideas of coherent storage of optical pulses [3] by considering the behavior of dark-state polaritons in an atomic medium where transparency is allowed via VIC. In our system, the role of the coupling field is replaced by the interaction between the atomic sublevel pathways where destructive interference of spontaneously emitted photons will lead to transparency. Previous investigations on coherent storage of pulses in resonant coherent media usually require a second laser pulse to create coherence to control the storage and retrieval processes. In the case analyzed in this paper, coherence can be created and preserved via a dissipative process, therefore requiring no additional coupling field to store the probe pulse [32]. In contrast with the case of Λ-type atoms, we will show that in the low excitation limit and adiabatic following, a shape preserving dark-state polariton can be obtained with a group

* Corresponding author. Tel.: +34 91 394 6856; fax: +34 91 394 6885.
E-mail address: ferpo@fis.ucm.es (F. Carreño).

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velocity that can be manipulated by varying the atomic splitting between the two upper atomic sublevels. In addition, we consider the application of a standing-wave field (SW) which leads to a periodic modulation of the dispersive properties of the medium allowing the obtention of stationary light [37,38]. Therefore we will be able to manipulate coherently the retrieved pulse. Recently, an important step towards light storage was achieved by employing coupling fields in a SW which induce a photonic bandgap in the medium. Such stationary light pulses may be used to devise interesting applications such as frozen light [39], all-optical switching and routing [40], and dynamically controllable photonic bandgap [41–43]. In the present paper, the addition of a control field coupled to an auxiliary atomic level, leads to a strong cross-Kerr effect between the probe and the control field, in a similar way to N-type atoms [44,45]. Thus, the current system can be considered as a $V-\Lambda-$type atom. The cross-Kerr effect can be exploited to create a refractive index change via cross-phase modulation and generate quasi-stationary pulses of light previously stored via vacuum-induced coherence. The main difference between this proposal and other systems previously considered (Λ-like systems) relies in the fact that in the current system the control field does not participate in the creation of the transparency. The control field merely produces a small disturbance of the EIT conditions while maintaining the system close to transparency.

In the SW configuration, higher-order momentum components of spin and optical coherences are expected to arise due to coherent scattering of the forward and backward propagating components of a probe field. The description of light pulse propagation in the presence of SW driving fields should take into account the contribution of these higher-order momentum components. In view of this, we shall investigate the optical response of ultra-cold four-level atoms driven by a stationary SW coupling field and a time-dependent probe field. Starting from the atomic steady-state susceptibility experienced by the probe, we first examine in Section 2 the optical response of a periodically modulated medium by using the transfer matrix method, we obtain the reflectance of the system. In Section 3 a linear analysis is performed in the adiabatic and weak-field limit which allows us to derive the equations of motion for the forward and backward components of the probe field. Next, we revisit the performance of the system as a optical memory in the absence of the control field, which allows us to devise how the addition of the far-detuned control field can be used to produce stationary light pulses within the medium. Then we resort to solve a reduced set of the Bloch equations in combination with the Maxwell propagation equation of the probe field without introducing any perturbation approximation. Our study deals with numerical solutions of these Maxwell–Liouville equations in the presence of a SW coupling field such as considered by [46], and does not invoke the secular approximation. Section 4 summarizes the main conclusions.

2. Theoretical model

We consider an atomic system of length L composed of four-level atoms as shown in Fig. 1. It has two intermediate levels , $|2\rangle$, and $|3\rangle$, which are coupled by the same vacuum modes to the lower level $|1\rangle$. The resonant frequencies between the levels $|2\rangle$, $|3\rangle$ and the ground level $|1\rangle$ are ω_{31}, and ω_{32}, respectively. Note that $\omega_{31}-\omega_{21}=\omega_{32}\equiv 2\Delta$, ω_{32} being the frequency separation of the excited levels. The spontaneous decay rates from the excited atomic levels $|2\rangle$, and $|3\rangle$ to the ground level $|1\rangle$ are labeled as γ_2, and γ_3 respectively and the spontaneous decay rate of the level $|4\rangle$ to the intermediate levels $|2\rangle$ and $|3\rangle$ is γ_4. A weak probe field $\hat{E}$ of frequency ω_p couples the ground level $|1\rangle$ with two intermediate atomic levels $|2\rangle$ and $|3\rangle$. This field is given by

$$\hat{E}=\frac{1}{2}\sqrt{\frac{2\hbar\omega_p}{\epsilon_0 V}}\hat{E}_p(z,t)e^{-i\omega_p t}+c.c. \quad (1)$$

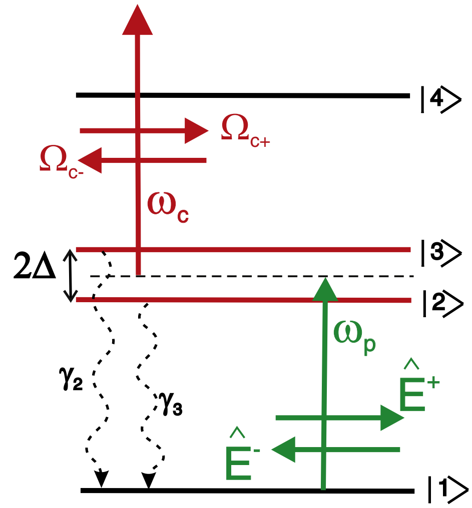

Fig. 1. Four-level scheme in the $V-\Lambda$ configuration. Forward and backward propagating control fields with Rabi frequencies fields $\Omega_{c\pm}$ and a weak signal field $\hat{E}_{\pm}$.

The quantum field is interacting with the transitions $|2\rangle\rightarrow|1\rangle$ and $|3\rangle\rightarrow|1\rangle$ with coupling constants g_2 and g_3 defined as

$$g_m=\sqrt{\frac{\omega_p}{2\hbar\epsilon_0 V}}\left(\vec{\mu}_{m1}\cdot\hat{e}_p\right)(m=2,3), \quad (2)$$

$\hat{e}_p$ being the unitary polarization vector of the quantum probe field and $\vec{\mu}_{m1}(m=2,3)$ stands for the electric dipole moments of the transition $|m\rangle\rightarrow|1\rangle$. We assume that the two intermediate levels $|2\rangle$ and $|3>$ are coupled through the same vacuum modes to the ground level $|1\rangle$, which results in vacuum-induced coherence effects arising from spontaneous emission.

In addition, two counter-propagating control fields with angular frequency ω_c couple the intermediate sublevels $|2\rangle$, and $|3\rangle$ to the upper level $|4\rangle$. The corresponding Rabi frequencies are $\Omega_{c2}=\mu_{42}E_c/2\hbar$ and $\Omega_{c3}=\mu_{43}E_c/2\hbar$, $\mu_{4j}(j=2,3)$ being the electric dipole moments of the transition $|j\rangle\rightarrow|4\rangle(j=2,3)$. The total control field can be expressed as

$$\Omega_c(z,t)=\left(\Omega_{c+}e^{ik_cz}+\Omega_{c-}e^{-ik_cz}\right)e^{-i\omega_c t}+c.c, \quad (3)$$

where Ω_{c+} and Ω_{c-} represent the Rabi frequency amplitudes of the forward and backward plane-wave components, respectively, which are assumed to be real without loss of generality.

To perform a quantum analysis of the light–matter interaction it is useful to use locally averaged atomic operators. We take a length interval Δz over which the slowly varying field amplitudes do not change much, containing $N_z=NA\Delta z$ atoms, N being the atomic density and A is the cross-sectional area of the pulses and we introduce

$$\hat{\sigma}_{\alpha\beta}(z,t)=\frac{1}{N_z}\sum_{j=1}^{N_z}\hat{\sigma}^j_{\alpha\beta}(\alpha,\beta=1,2,3,4), \quad (4)$$

$\sigma^j_{\alpha,\beta}=|\alpha\rangle_{jj}\langle|\beta|\;(\alpha,\beta=1,2,3,4)$ being the quasi-spin operators of the j-th atom. In the case $\alpha\neq\beta$ it denotes the flip operator of the j-th atom located at position z_j from the state $|\beta\rangle_j$ to $|\alpha\rangle_j$. The dynamics of the system is governed by a set of Heisenberg–Langevin equations

$$\frac{d\rho}{dt}=-\frac{i}{\hbar}[H_0+H_{ext},\rho]+\frac{1}{2}\mathcal{L}\rho, \quad (5)$$